



# Crop residue open field burning in Pakistan; multi-year high spatial resolution emission inventory for 2000–2014

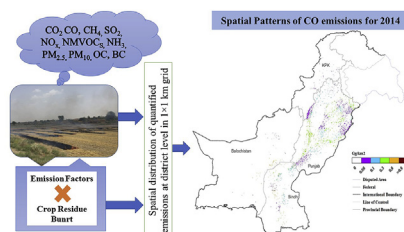
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## GRAPHICAL ABSTRACT



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## ABSTRACT

Over recent years, crop residue burning has become a widely practiced agricultural activity in developing countries due to varying economic and social reasons. To estimate current pollution generation from crop residue burning in Pakistan, an emission inventory was developed based on district level crop production data from 2000 to 2014. Spatial distribution of quantified emissions was achieved by using MODIS Active Fire Data (MOD/MYD14A1) at 1-day temporal and  $1 \times \text{km}$  spatial resolutions. The fire occurrences were extracted over agricultural land using land cover data provided by European Space Agency/Climate Change Initiative (ESA/CCI) at 300 m spatial resolution for 2000 to 2014. Results show that CO emissions have increased by 40% at an average annual rate of 2.7% from 1.16 Tg in 2000 to 1.63 Tg in 2014 and increase in emissions of  $\text{CO}_2$ ,  $\text{CH}_4$ , NMVOCs,  $\text{N}_2\text{O}$ ,  $\text{NH}_3$ ,  $\text{SO}_2$ ,  $\text{NO}_x$ ,  $\text{PM}_{2.5}$ ,  $\text{PM}_{10}$ , OC and BC ranged between 37%, to 63% during same period. Spatially, CO emissions were more significant in districts of Punjab and Sindh provinces with intensive agricultural activities as compared to other areas of Pakistan with highest emission grids located in Muzaffargarh, Jafferabad, and Noushahro Feroze districts. Crop residue burning exhibited similar trend with highest emissions in June followed by February and November over 15-year period. The emissions for most of the considered pollutants were comparable to the limited previous studies available. Finally, the study conducted provides better understanding regarding spatial and temporal patterns of crop residue burning across Pakistan and can be utilized for air quality modeling and management with higher accuracy.

## 1. Introduction

Increasing anthropogenic emissions are accelerating phenomenon

of climate change (Andreae, 2001; IPCC, 2007), besides exacerbating the air quality and consequently impacting human health and ecosystems (Fernandez et al., 2001; Johnson and Bryden, 2005; Bond et al.,

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2013; Wei et al., 2015). Asian region being the most populated as well as the largest contributor, tends to increase these anthropogenic emissions more significantly in the near future as compared to North America and Europe (Akimoto, 2003; Ohara et al., 2007). Being one of the most ancient anthropogenic air pollution sources, biomass burning was first recognized in late 1970s (Crutzen et al., 1979) and its role in atmospheric chemistry was duly highlighted. It is considered to be one of the major sources of aerosol pollutants and trace gases in local as well as in regional and global atmosphere due to its long range transport (Andreae, 2001; Permadi and Kim Oanh, 2013; Li et al., 2016). Biomass burning includes savanna, forest and peat land fires, open burning of crop residues and biofuel burning (Van Der Werf et al., 2010; Akagi et al., 2011). Streets et al. (2003b) reported that 34% of total biomass burned in Asia comprises of crop residue burning.

Crop residue burning is a common practice in the developing countries as farmers are not well aware of the benefits associated with its alternative uses, making open burning an alluring choice for its disposal particularly in Asian countries (Permadi and Kim Oanh, 2013). It is estimated that small agricultural fires led to an increase in global surface burned area from 345 Mha/yr in 2001 to 464 Mha/yr in 2010 (Randerson et al., 2012). Crop residues are burned for a number of reasons including clearing the land for upcoming cultivation, control of weeds and providing nutrients for the next crop cycle (Dennis et al., 2002; Huang et al., 2012; Irfan et al., 2014).

Apart from the benefits associated with crop residue burning, its emissions impact the atmospheric chemical composition consequently affecting the radiation balance of Earth's atmosphere. Quantification of this impact has been widely investigated and reported in recent past. Carbon dioxide emitted from large scale crop residue burning has major implications on the carbon cycle (IPCC, 2007; Wiedinmyer et al., 2011) while other gaseous pollutants such as CO, SO<sub>2</sub> and NO<sub>x</sub> act as precursors in development of tropospheric ozone. The increase in tropospheric ozone concentration affects the lungs adversely and leads to the formation of photochemical smog, reducing visibility (Chen and Watson, 2017). Being episodic in nature, crop residue burning occurs in particular months leading to enhanced PM concentrations temporally (Crutzen and Andreae, 1990). Higher PM concentration impacts humans' respiration capacity (Dvornich et al., 2009; Samet et al. 2009; Li et al., 2013) and is reported to be a cause of cardiopulmonary morbidity with mortality of 3.7 million people during 2010 (WHO, 2012). Black Carbon (BC) emitted due to intense biomass burning results in enhanced absorption of visible light by atmosphere, causing warming effect. Whereas Organic Carbon (OC) emitted, causes surface cooling due to scattering of light (Ramanathan et al., 2005).

Relatively less work is done on quantification of emissions from crop residue burning in developing countries of world including Pakistan. Pakistan's economy is largely dependent on agricultural production and field burning plays an important role in atmospheric pollution in the region. Streets et al. (2003b) estimated that almost 750 Tg of biomass was burned in 2000 in Asia out of which, 250 Tg was crop residue. The share of Pakistan in crop residue burning was almost 10 Tg which is relatively less as compared to other countries of Asia, however, it cannot be ignored. Evaluating the extent and patterns of pollutants and greenhouse gas emissions from residue burning is of great importance in air quality monitoring and management. Hence a precise and high-resolution emission inventory for open burning of crop residues in fields is needed.

Conventionally, emission inventories of crop residue open burning have been developed either using top-down or the bottom-up approaches. Top-down approach aims at developing the emission inventory on the basis of (national or regional) level activity data (usually quantified by satellite monitoring), incorporating fuel load and combustion efficiencies (Duncan et al., 2003; Korontzi et al., 2006; Shi and Yamaguchi, 2014; Wu et al., 2018). However, this approach involves higher uncertainties, mainly due to coarse temporal and spatial resolution of satellite observations (Roy et al., 2008). In bottom-up

approach, on the other hand, emissions are quantified by using local (usually district) level monitored activity data and the corresponding emission factors (Seiler and Crutzen, 1980). Although bottom up approach for emission inventory development involves over all less uncertainties in the estimates (given the local data is accurate), it requires high resolution activity data as input (Kanabkaew and Oanh, 2011; Zhang et al., 2013). Earlier, emission inventories have been established by distributing the total emissions to grids either uniformly or according to the weighting of population or harvested area (Streets et al., 2003b; Gadde et al., 2009; Zhang et al., 2013). More recent approach is to use satellite based active fire observations to distribute the over all emissions over area and period of interest (Van Der Werf et al., 2010), which has helped in establishing emission inventories at finer spatial and temporal resolutions (Qiu et al., 2016). It is to be noted here that polar orbiting satellites can not record the active fires occurring out of time-window of their pass over a particular location or the fires covered by the clouds, which incorporates uncertainty in spatio-temporal allocation of emission (H. K. et al., 2018). Besides active fire data used for temporal and spatial allocation of emissions, satellite retrieved burnt area observations have also been used to quantify the biomass burnt. However, due to coarse resolution, satellite observations tend to ignore small fires or misinterpret clusters of small fires as one big fire (Huang et al., 2018). The uncertainty in burnt area data products become a serious limitation to be used as means of quantification of biomass burnt for places like Pakistan where average farm size is too small (0.025 km<sup>2</sup>).

Due to increasing smog episodes in the recent past in the region, with reported contribution of agricultural residue burning in the events (P. Singh and Kaskaoutis, 2014; Kim Oanh et al., 2018), regional governments have devised and are trying to implement the policies to manage the issue (Smog Policy and Action Plan for Control, 2017). Keeping this in view, a detailed emission inventory for Pakistan was needed. Previously, emissions from crop residue burning were estimated using bottom-up approach for Pakistan (Streets et al., 2003b; Irfan et al., 2014, 2015). Reliability of emission factors, dry matter content, grain to straw ratio, combustion efficiency and portion of crop residue burned on field is a major challenge in developing an accurate emission inventory with bottom-up approach. However, values for emission factors, grain to straw ratios and dry matter content used in reported studies (Streets et al., 2003b; Irfan et al., 2014, 2015) were not region specific. Moreover, in mentioned studies, the portion of crop residue burned on field was assumed to be 25% of the total generated amount which could cause errors in estimations and mislead policy-making. It has been reported that use of combine harvesters produces significantly higher amount of residue left on field for combustion as compared to manual harvesting and hence, quantification and incorporation of the two types of harvesting methods in emission estimates reduces errors (Yang et al., 2008; Mishra and Shibata, 2012). Irfan et al. (2014) for the first time determined emission factors for trace gasses and GHGs emitted from different crop residues for Pakistan, however, the results had not been utilized in developing emission inventories previously. In earlier reported studies, spatial resolution was either too low (0.25° in Streets et al. (2003b)) or it was presented in grids over districts of specified provinces irrespective of the land use (Irfan et al., 2015). Moreover, these inventories did not incorporate temporal resolution and were developed for a single year. In air quality modeling detailed emission inventory with high spatial and temporal resolution is preferred. Understanding inter-annual variations in crop residue burning is important while using air quality models for air quality management and climate change issues.

In this study a historical emission inventory is developed 15 years (2000–2014) having 1 × 1 km spatial and 1-day temporal resolution from 2000 to 2014. Prior to developing an inventory, primary data including production statistics of four major crops (wheat, rice, maize and sugarcane) was collected for 126 districts from yearly statistical book prepared by Pakistan Bureau of Statistics (PSB). The crop

production data is collected on district level by conducting multiple surveys on different stages of crop growth cycles by respective provincial agricultural departments. The data is then compiled by respective provincial agriculture statistics coordination board and finally by PBS. Other parameters such as emission factors, grain to straw ratio, dry matter content and combustion efficiency were taken from the literature. Data regarding method of harvesting was obtained from a survey conducted by the World Bank for establishing biomass atlas for Pakistan (World Bank, 2016). For gridding the quantified emissions MODIS active fire data of MOD/MYD14A1 was used which is provided at 1 km resolution with daily fire occurrences. These fire occurrences were then extracted over agricultural land using land cover data provided by ESA/CCI.

## 2. Methodology

### 2.1. Study area

Pakistan is the sixth most populated country in the world, with an average annual growth rate of 2.4% and having a population of 207.8 million (Population Census, 2017). Geographically Pakistan covers north-western part of Asia housing India to its east, China in the north-east while Iran to its West and Afghanistan to its north-west. Administratively, Pakistan consists of five provinces which include Punjab, Sindh, Khyber Pakhtunkhwa (KPK), Balochistan and Gilgit-Baltistan. Every province is further sub-divided into divisions which are further divided in districts and tehsils (sub-districts). Fig. 1 shows the map of

Pakistan with districts names. Each district is assigned a number, which will be used in this paper for reference. Agriculture is the backbone in the economy of Pakistan with almost 70% of population earning livelihood from agricultural activities (Irfan et al., 2015). This study involves all provinces and their respective district except Gilgit-Baltistan (due to lack of data availability). Punjab and Sindh dominate agricultural activities with least contribution from KPK, Balochistan. Thirty-seven districts of Punjab, twenty-three of Sindh, thirty-five of KPK and thirty districts of Balochistan are included in the study. Wheat straw, rice straw, sugarcane leaves and maize straw are the common forms representing open burning of crop residues. Crop cultivation and harvesting patterns in Pakistan are shown in Fig S1 (SI).

The study comprises of two phases; district-wise emission estimation for Pakistan and secondly, mapping of these emissions at 1 km × 1 km spatial and one-day temporal resolution. Steps-wise details of the two phases are discussed as follows:

### 2.2. Estimating emissions

The emissions from selected crop residues were calculated using eq. (1):

$$E_{i,j} = EF_{i,j} \times C_{m,j} \times 10^{-9} \quad (1)$$

Where,  $E_i$  is the emission (Gg) of pollutant  $i$  emitted from burning of crop  $j$  residue,  $EF_{i,j}$  (g/kg) is crop  $j$  specific emission factors of pollutant  $i$ ,  $C_{m,j}$  (kg) is the amount of crop  $j$  residue burned in district  $m$ .

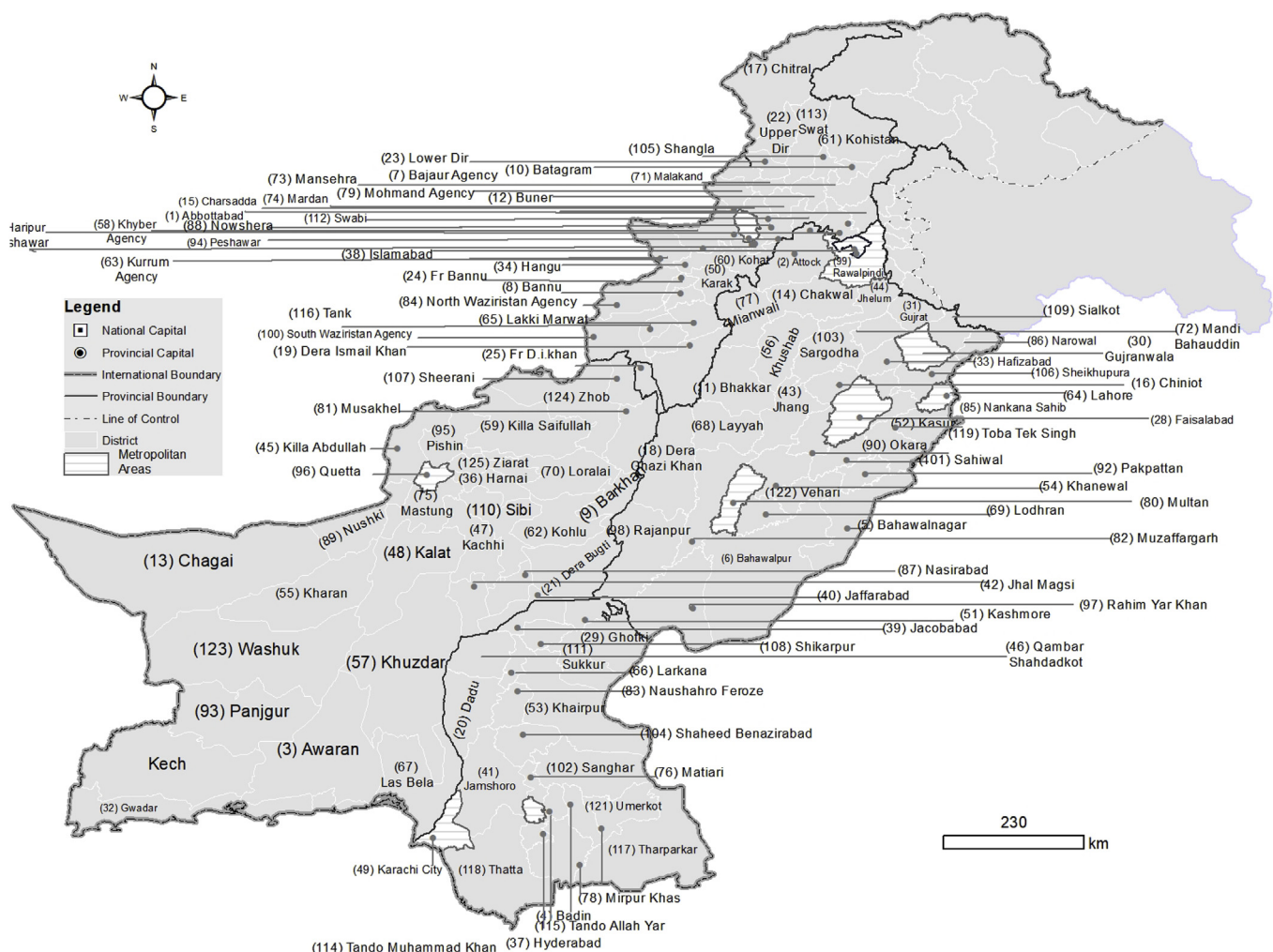


Fig. 1. Map of Pakistan with district names and numbers to be referred in this study.

**Table 1**  
Parameters used in eq. (2) for estimation of crop residue burned on Fields.

| Crops            | Grain to straw ratio  | Combustion efficiency | Dry matter content    |
|------------------|-----------------------|-----------------------|-----------------------|
| Wheat straw      | 1.75 <sup>a</sup>     | 0.86 <sup>b</sup>     | 0.83 <sup>a,c</sup>   |
| Rice straw       | 1.5 <sup>e</sup>      | 0.89 <sup>a</sup>     | 0.85 <sup>a,e,g</sup> |
| Maize straw      | 2.0 <sup>c,d</sup>    | 0.92 <sup>d,b</sup>   | 0.40 <sup>b,a</sup>   |
| Sugarcane leaves | 0.24 <sup>b,a,f</sup> | 0.68 <sup>b</sup>     | 0.71 <sup>a</sup>     |

<sup>a</sup> (Turn et al., 1997).

<sup>b</sup> (Streets et al., 2003b).

<sup>c</sup> (Streets et al., 2003c).

<sup>d</sup> (Iqbal and Goheer, 2008).

<sup>e</sup> (Gadde et al., 2009).

<sup>f</sup> (Kanabkaew and Oanh, 2011).

<sup>g</sup> (Irfan et al., 2015).

### 2.2.1. Quantification of district-wise residue burned

Crop residue burned on the field mainly depends on crop production, grain to straw ratio, dry matter content, portion of crop residue burned on field and the combustion efficiency. Grain to straw ratio refers to mass ratios of the crop product to field residue for field crops (Wang, et al., 2012). Thus, total amount of crop residue burned was calculated using eq. (2) (Li et al., 2016).

$$C_{m,j} = P_{m,j} \times G \times D \times \omega \times \delta \quad (2)$$

Where:  $C$  denotes the total amount (kg) of crop type  $j$  residue burned in

district  $m$ ,  $P_{m,j}$  represents the annual production of crop  $j$  in district  $m$ ,  $G$  is the grain to straw ratio,  $D$  denotes the dry matter content of each of the crop while,  $\omega$  shows the amount portion of crop residue that is left on field for burning and  $\delta$  is the combustion efficiency. Values of  $G$ ,  $D$  and  $\delta$  used in eq. (2) are obtained from previous studies for crops in consideration and are described in Table 1.

The portion of crop residue burned in field is an important factor to be determined. Field surveys have revealed that the amount of crop residue left on field for burning is greater with mechanical harvesting as compare to manual harvesting which encourages farmers for agricultural burning (Mishra and Shibata, 2012; Li et al., 2015). In this study, eq. (3) was used to calculate the portion of residue burned on field.

$$\omega_m = A_m \times \alpha_m + B_m(1 - \alpha_m) \quad (3)$$

Where  $\alpha_m$  is the proportion of crop harvested mechanically in district  $m$  (and hence,  $1 - \alpha_m$ , is that harvested manually), and  $A_m$  and  $B_m$  are the proportions of the residues left on field for burning for mechanical and manual harvesting respectively. Values for  $\alpha_m$ ,  $A_m$  and  $B_m$  were extracted from the field surveys conducted earlier (World Bank, 2016) in 44 districts of Pakistan. Use of combined harvester is usually practiced in large fields (by resourceful farmers) in plain areas whereas farmers with limited resources usually opt for manual harvesting, making  $\alpha_m$  variable over the districts. However, values of these parameters for the districts which were not included in report, were replaced by known values of the nearest district, as agricultural practices are deemed similar with in nearby districts. Fig. 2 shows the values of portion burned

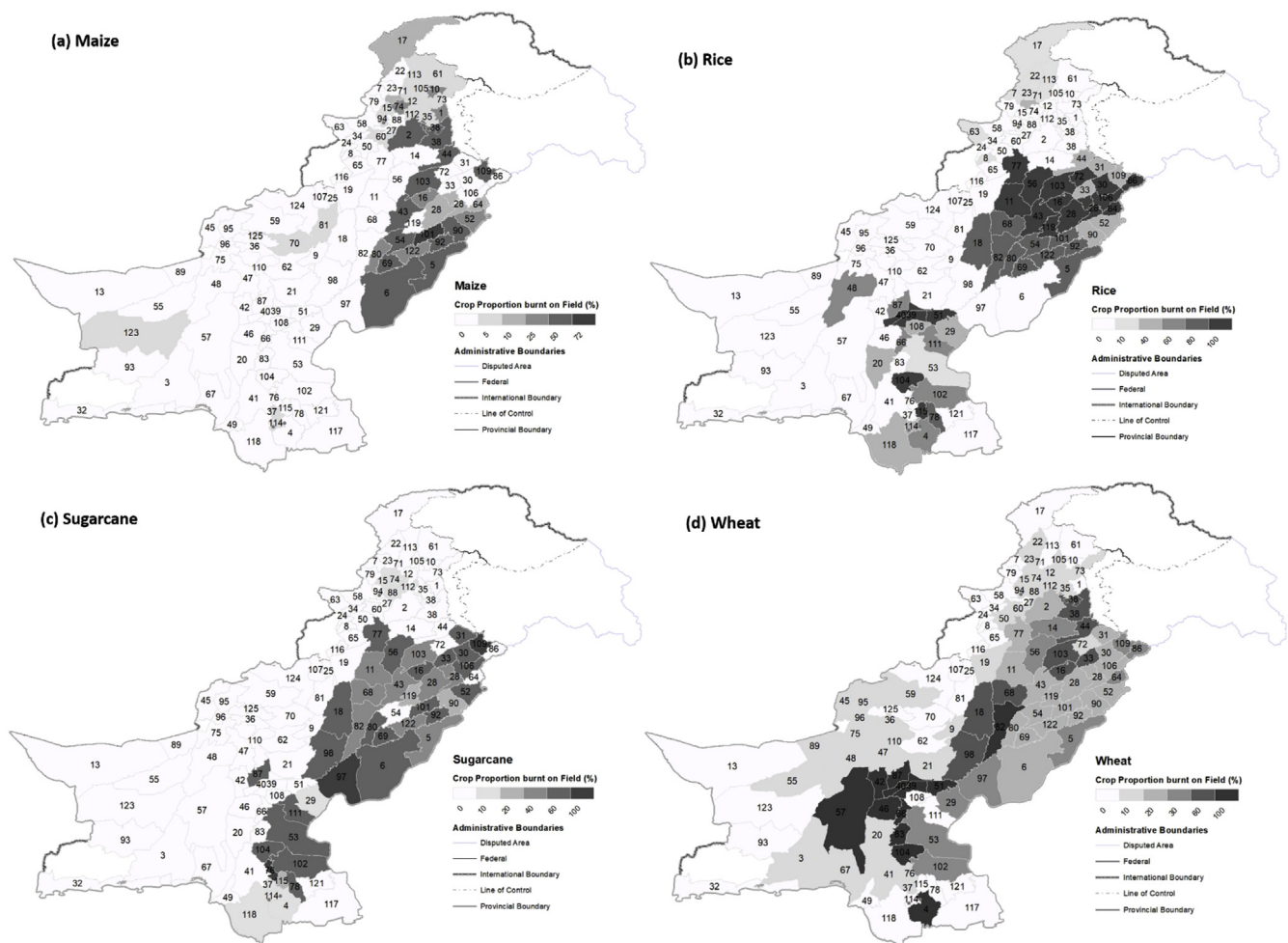


**Fig. 2.** Portion of crop residues burned on field in various districts of Pakistan, (a) Maize, (b) Rice, (c) Sugarcane, (d) Wheat. Note that numbers 1–126 represents district names and details are provided in Table S1 (Supplementary Information, SI).

**Table 2**  
Emission factors (eq. (1)) selected for this study.

| Crops           | CO <sub>2</sub>     | CO                  | CH <sub>4</sub>   | NMVOcs            | N <sub>2</sub> O  | NH <sub>3</sub>   | SO <sub>2</sub>    | NOx                   | PM <sub>2.5</sub> | PM <sub>10</sub>  | OC                 | BC                |
|-----------------|---------------------|---------------------|-------------------|-------------------|-------------------|-------------------|--------------------|-----------------------|-------------------|-------------------|--------------------|-------------------|
| Rice Straw      | 1105.2 <sup>a</sup> | 53.2 <sup>c,a</sup> | 5.82 <sup>b</sup> | 6.05 <sup>a</sup> | 0.07 <sup>g</sup> | 2.2 <sup>b</sup>  | 0.38 <sup>c</sup>  | 3.16 <sup>d,e,f</sup> | 12.1 <sup>a</sup> | 3.7 <sup>d</sup>  | 10.53 <sup>a</sup> | 0.49 <sup>a</sup> |
| Wheat Straw     | 1557.9 <sup>c</sup> | 141.2 <sup>c</sup>  | 3.55 <sup>i</sup> | 7.5 <sup>h</sup>  | 0.07 <sup>h</sup> | 0.37 <sup>h</sup> | 0.85 <sup>h</sup>  | 1.12 <sup>c</sup>     | 7.58 <sup>h</sup> | 5.74 <sup>k</sup> | 3.46 <sup>i</sup>  | 0.42 <sup>j</sup> |
| Maize Straw     | 1261.5 <sup>c</sup> | 114.7 <sup>c</sup>  | 4.4 <sup>h</sup>  | 10 <sup>h</sup>   | 0.14 <sup>h</sup> | 0.68 <sup>h</sup> | 0.44 <sup>h</sup>  | 3.06 <sup>a</sup>     | 11.7 <sup>h</sup> | 6.21 <sup>k</sup> | 2.79 <sup>a</sup>  | 0.69 <sup>a</sup> |
| Sugarcane Trash | 1152.5 <sup>a</sup> | 40.1 <sup>a</sup>   | 0.4 <sup>i</sup>  | 2.2 <sup>i</sup>  | 0.07 <sup>g</sup> | 1.0 <sup>i</sup>  | 0.216 <sup>m</sup> | 2.01 <sup>c</sup>     | 4.12 <sup>a</sup> | 5.65 <sup>a</sup> | 1.25 <sup>a</sup>  | 1.22 <sup>a</sup> |

<sup>a</sup> (Zhang et al., 2013).  
<sup>b</sup> (Li et al., 2016).  
<sup>c</sup> (Zhang et al., 2008).  
<sup>d</sup> (Kadam et al., 2000).  
<sup>e</sup> (Irfan et al., 2014).  
<sup>f</sup> (Gadde et al., 2009).  
<sup>g</sup> (Andreae, 2001).  
<sup>h</sup> (Li et al., 2007).  
<sup>i</sup> (Sahai et al., 2007).  
<sup>j</sup> (CAO et al., 2008).  
<sup>k</sup> (Turn et al., 1997).  
<sup>l</sup> (Dennis et al., 2002).  
<sup>m</sup> (Kanabkaew and Oanh, 2011).

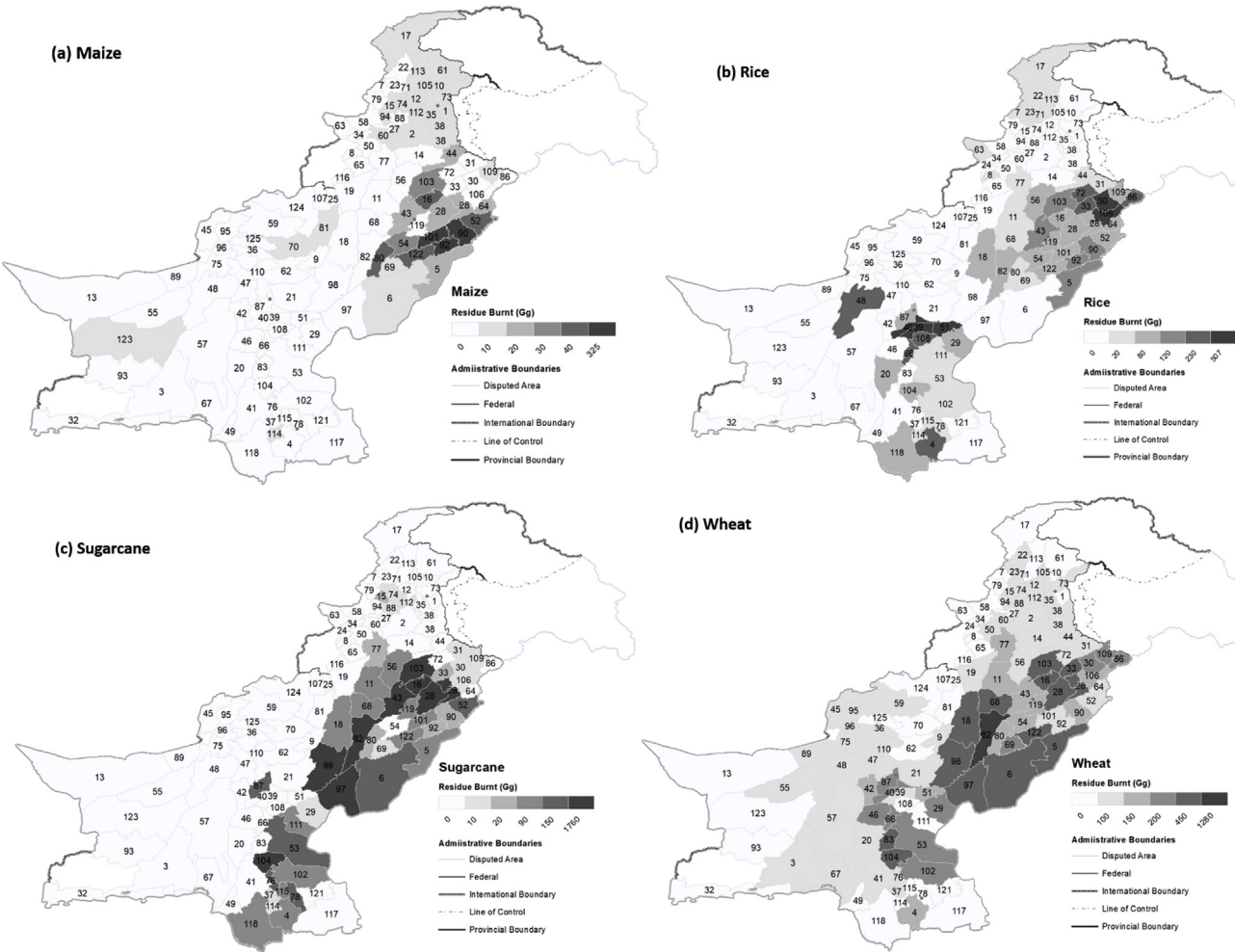


**Fig. 3.** Quantities of crop residues subjected to open burning in fields across Pakistan (a) Maize, (b) Rice, (c) Sugarcane, (d) Wheat.

on field of Maize, Rice, Sugarcane and Wheat. Fig. S2 (SI) shows a detailed and coloured version of the same values for better understanding of the readers.

2.2.2. Emission factors

Emission factor is the basic parameter in developing the emission

inventory. Due to lack of locally developed emission factors for Pakistan, most of the emission factors were obtained from regional and foreign studies after extensive literature review. Previously, Pakistan specific emission factor values for few pollutants (SO<sub>2</sub>, NO<sub>x</sub>) and crops (rice straw) have been reported (Irfan et al., 2014). For wheat, majority of the emission factors for this emission estimation, were taken from

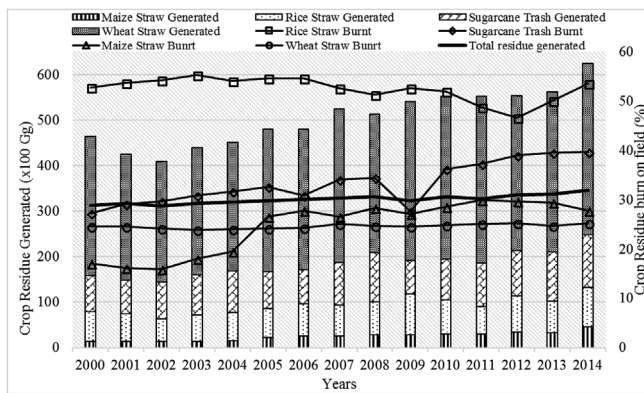


Fig. 4. Yearly variation in the amount of crop residue generated (bars, scaled on left Y-axis) and percentage subjected to burning (Lines graphs, scaled on right Y-axis).

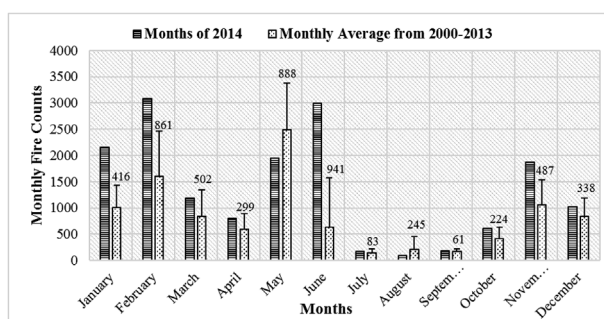


Fig. 5. Monthly variation in MODIS fire Counts with yearly average.

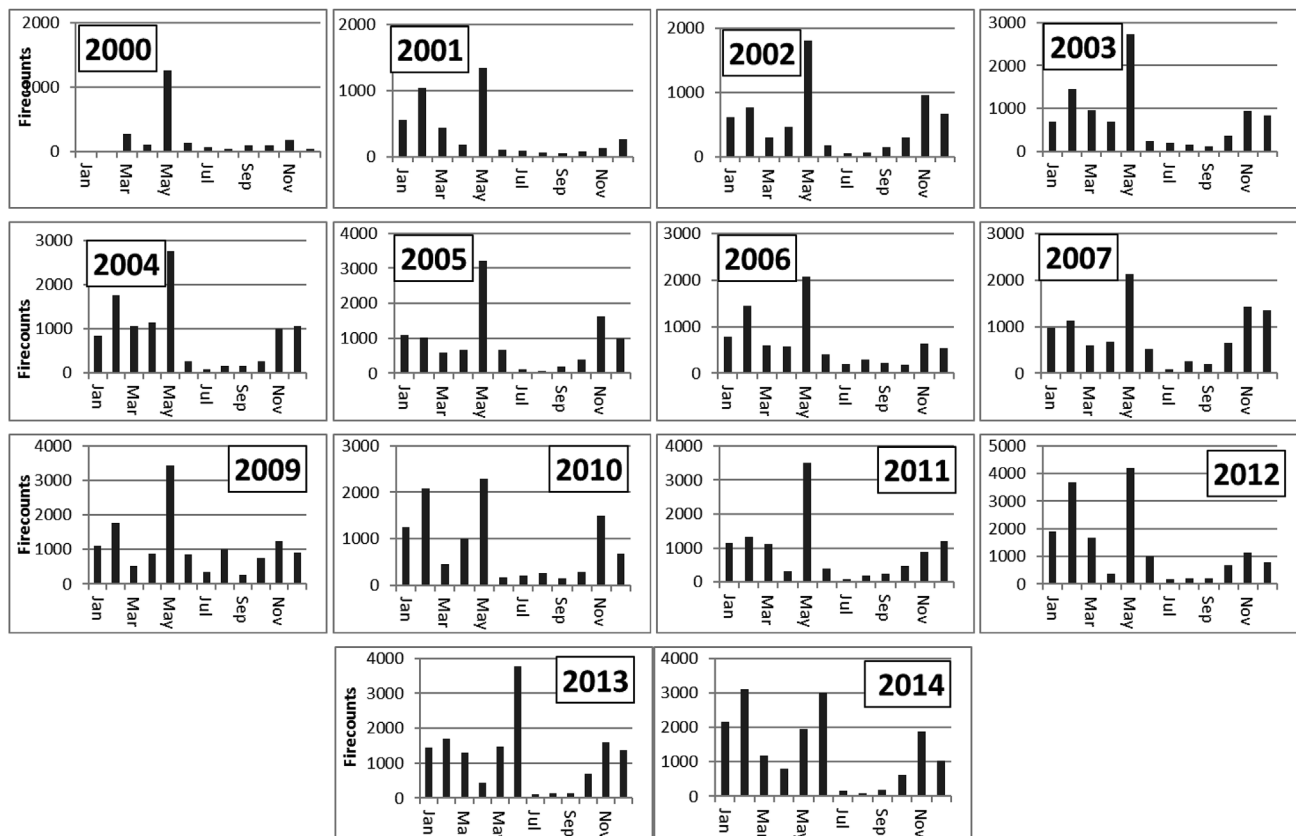


Fig. 6. Variation in MODIS fire Count monthly averages over 15 years (2000–2014).

studies reported from India (Sahai et al., 2007) as agricultural practices and socio-economic/environmental conditions of the two countries are similar. For rest of the emission factors, priority was given to the those reported from similar developing countries (recently) over others, to make them as representative as possible. Table 2 presents the emission factors selected to be used in this study whereas Table S2 shows the ranges of emission factors for selected pollutants reported previously.

### 2.3. Spatial and temporal allocation of pollutants

For the spatial and temporal allocation of pollutants for emission inventory development, MODIS active fire data (MOD/MYD14A1) recorded during 2000–2014 was used ([https://lpdaac.usgs.gov/dataset\\_discovery/modis/modis\\_products\\_table](https://lpdaac.usgs.gov/dataset_discovery/modis/modis_products_table)). The data product had a  $1 \text{ km} \times 1 \text{ km}$  resolution with one observation per day for each TERRA and AQUA satellites.

Land cover data was downloaded from (<http://maps.elie.ucl.ac.be/CCI/viewer/>) for identification of croplands. The CCI-LC global land cover maps are on annual basis with a spatial resolution of 300 m. These maps categorize land cover into 22 classes using LCCS (Land Cover Classification System) classifiers. MODIS active fire that lie under the land cover classified as Irrigated croplands, Rainfed croplands or Mosaic cropland (> 50%) were recognized as crop residue burning in fields. The emissions were gridded using eq. (4).

$$E_i = \frac{FC_i}{FC_m} \times E_m \quad (4)$$

Where  $E_i$  denotes the emission in  $i$ th grid while  $FC_i$  stands for the cropland fire counts detected in  $i$ th grid,  $FC_m$  is the total cropland fire counts in district  $m$ , and  $E_m$  is the total annual emissions calculated from crop residue burning in district  $m$  using eq. (1).

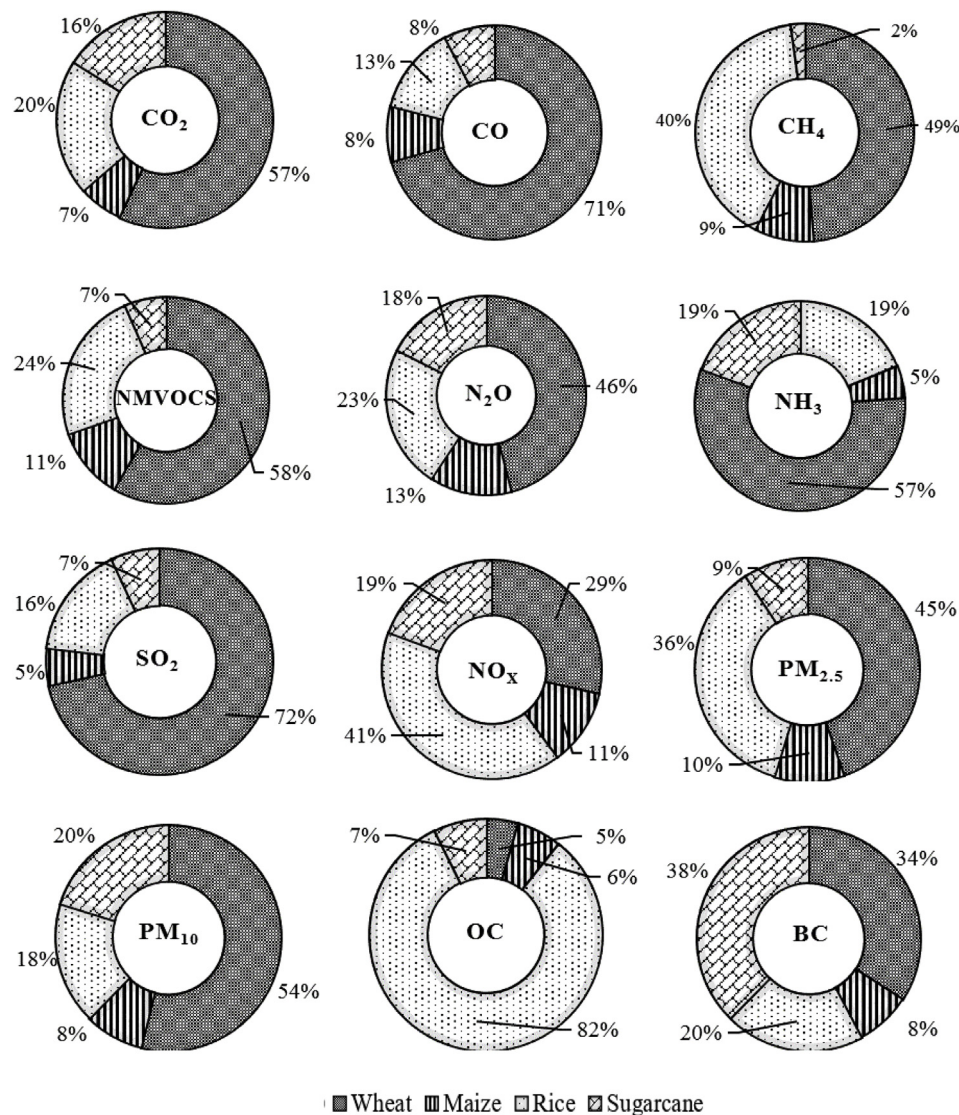


Fig. 7. Contribution of each crop in emissions in 2014.

### 3. Results and discussions

#### 3.1. Crop residue generated and burned on field

Total residue generated for selected crops was 62.47 Tg out of which 20 Tg was burned on fields during 2014. Largest share (48%) was that of wheat, followed by rice straw and sugarcane leaves (23% each). Maize straw contributed around 6%. Fig. 3 (and Fig. S3, in SI for better viewing) shows district-wise residue generation across Pakistan in 2014.

Maize burning dominates in districts 90 (Okara), 101 (Sahiwal) and 92 (Pakpattan) of Punjab province with least contribution from districts in KPK, Balochistan and Sindh provinces. Results for rice revealed that most of the residue generated is burned on fields in district 30 (Gujranwala), 106 (Sheikhupura), 39 (Jacobabad), 51 (Kashmore) and 40 (Jafferabad) where mechanized harvesting is adopted. In districts of lower Punjab, due to utilization of manual harvesting the residue generated is less which leads to less burning practice and similar trend is observed in other districts where manual harvesting is practiced. Sugarcane leaves dominate in post-harvest burning with most of the residue generated burned on fields include 103 (Sargodha), 16 (Chiniot), 28 (Faisalabad), 43 (Jhang), 82 (Muzaffargarh) and 98 (Rajanpur) in Punjab, 87 (Nasirabad) and 104 (Shaheed Benazirabad)

in Sindh. Least contribution in residue burned comes from the districts in KPK which include 74 (Mardan), 112 (Swabi), 15 (Charsadda) and 88 (Nowshera). Wheat burning mainly occurs in all districts and it is estimated that almost 1280 Gg of residue was burned in district 82 (Muzaffargarh) alone in 2014.

Temporal trend of crop residue burned over 15 years (2000–2014) with variation in production is shown in Fig. 4. The total amount of residue generated from four crops in 15 years over Pakistan is 757 Tg while the residue left on field for burning is 228 Tg which is 30 percent of the total residue generated. The largest share (52%) in total residue generated was that of wheat followed by rice (24%), sugarcane (20%) and maize (4%). Large variation exists in each crop residue generation across districts over Pakistan due to varying cropping patterns, cropping intensity and productivity. Over the years wheat exhibited a continuous increasing trend of residue generation while its portion burned on field remained constant around 25%. Sugarcane, Maize and Rice showed a varying trend as compare to Wheat. Since wheat straw is used as fodder for animals, lesser percentage of the generated residue is burnt. Whereas, due to low nutritional value, rice straw is not used as animal feed. Moreover, due to crop rotational cycle, farmers get less time between rice harvesting and wheat cultivation, hence higher fraction of rice straw burnt in fields.

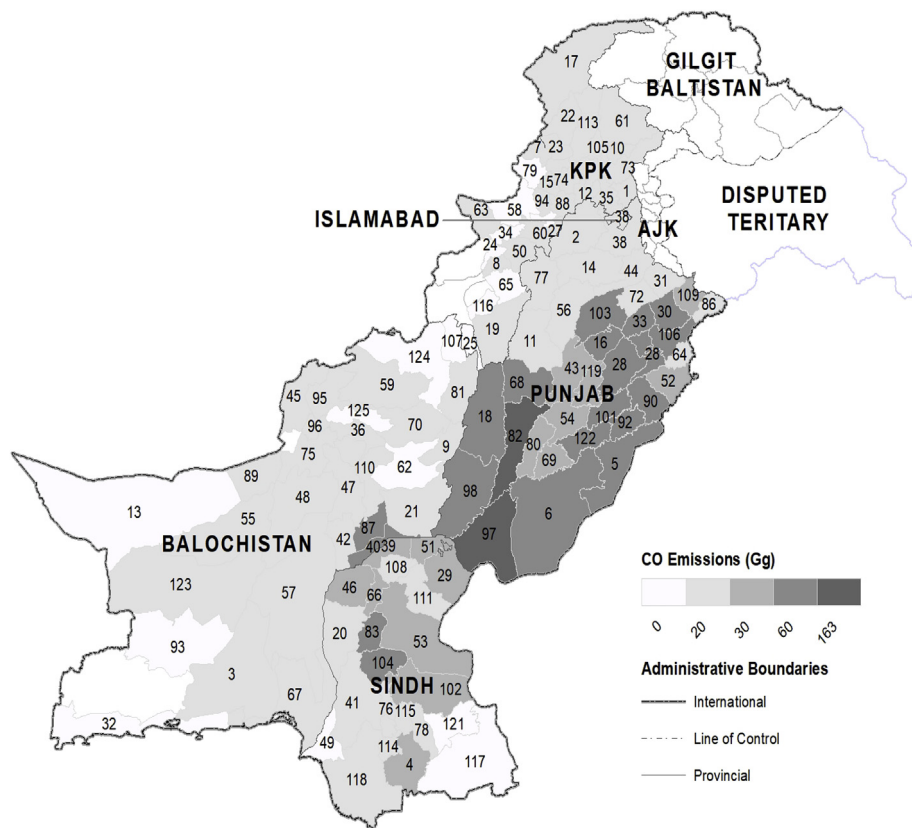


Fig. 8. District-Wise variations in CO emissions.

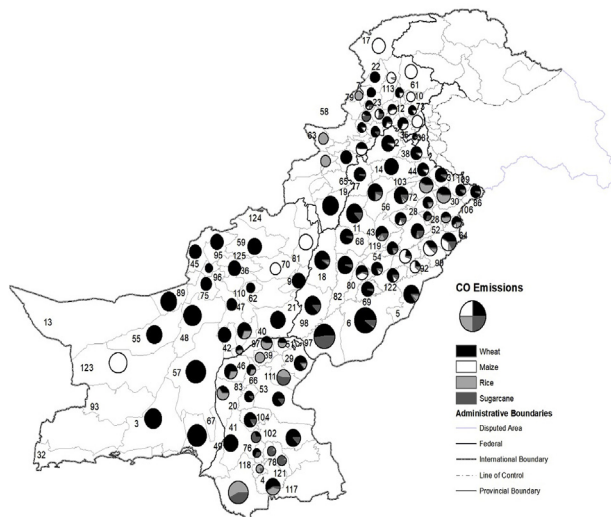


Fig. 9. District-Wise crop specific variations in CO emissions.

### 3.2. Spatial and temporal patterns in fire counts

The total fire counts extracted over croplands in Pakistan from 2000 to 2013 were 139915 whereas during 2014, the number was 16112. Monthly variation in fire counts during 2014, and past 14 years is shown in Fig. 5. The fire counts were more concentrated in the month of February (19%) followed by January (13%), June (18%) followed by May (12%), November (12%) and December (6%) during 2014. The monthly average over past 14 years was slightly different as compared to 2014 with most fire occurrences in May followed by February, November and December. The first peak observed in monthly variation of

fire counts is in February followed by January which refers to the harvesting season of sugarcane. The fire occurrences observed in the second period from April–June is mainly due to harvesting of wheat starting with early harvest in Sindh in April and ending in Punjab and KPK provinces till June. While the third peak observed is from November–December which refers to the harvesting of rice which is cultivated in early July. Mostly fire occurrences are observed in the harvesting season of wheat over the years. Fig. 6 shows the variation of monthly fire counts observed over study period (2000–2014). It is to be noted here that overall fire counts increased for all months significantly over the study period, depicting the gradual increase in the production.

### 3.3. Emissions inventories

#### 3.3.1. Emissions of PM, GHGs and other gaseous pollutants in 2014

Developed inventories provide emission estimates of 12 pollutants from four major crops and are shown in Fig. 12. District-wise variation in emissions of GHGs and other pollutants in 2014 are shown in Table S3. Agricultural (including fisheries and livestock) sector has been reported as the second largest GHG source (39%) after Energy (51%) in Pakistan (Khan, 2014). However, Mir et al. (2017) estimated the GHG emissions from fuel combustion in different sectors of Pakistan for year 2012 and reported energy (47.3 Tg CO<sub>2</sub> eq.), manufacturing industry (37.9 Tg) and transport (37.5 Tg) sectors to be causing higher GHG emissions than that of agricultural residue burning (four major crops considered) reported in this study (21 Tg) for same year. Agricultural residue burning has also been identified as second largest source contributing to organic carbon (OC) in PM<sub>2.5</sub> in urban areas of Pakistan (Stone et al., 2010), consequently making the air quality of bigger cities (e.g. Lahore) ranked amongst the worst globally. Similarly, emissions from crop residue burning, along with other anthropogenic activities, are reported to be significant enough to influence the variability of gaseous pollutants e.g. CO in the region (Rana et al., 2015). Combined

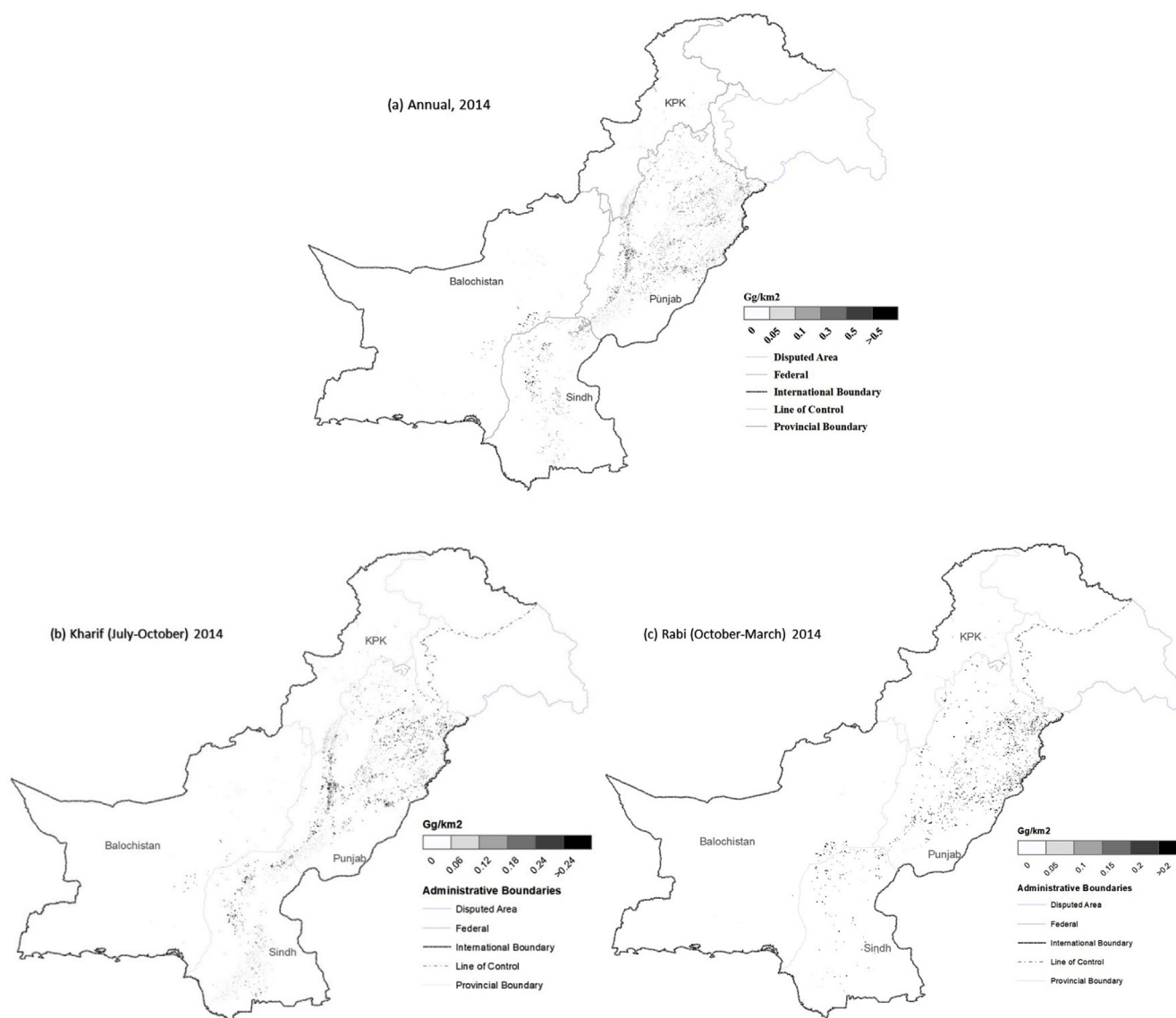


Fig. 10. Spatial distribution of CO emissions in  $1 \times 1$  km grid cell (a) annual, (b) Kharif and (c) Rabi seasons, 2014

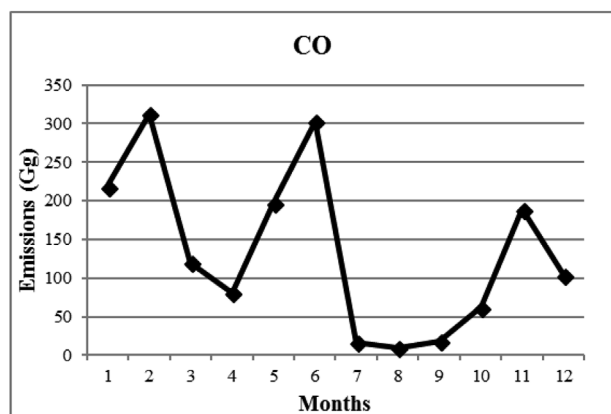


Fig. 11. Monthly variations in CO emissions from all considered crop types in 2014 (Gg).

with favorable meteorological conditions of low mixing height and low wind speeds in the Indo-Gangetic plain, the pollutants emitted by biomass burning during October–February, significantly contribute

towards near-ground-formation of thick haze, which covers the region from west to east (Badarinath et al., 2009; Mishra and Shibata, 2012; Pavel et al., 2014).

### 3.3.2. Contribution to pollutants from each crop

The contribution of the four crop types in pollutant emission in 2014 is given in Fig. 7. Wheat straw being the largest contributor to all of the pollutants emitted except for  $\text{NH}_3$ ,  $\text{NO}_x$ , OC and second largest contributor to BC. Rice straw was the largest contributor to  $\text{NH}_3$ ,  $\text{NO}_x$  and OC and second largest contributor to all other pollutants except BC. Open burning of sugarcane leaves was the largest contributor to BC emissions and third largest contributor to all pollutants except NMVOCs,  $\text{CH}_4$  and  $\text{PM}_{2.5}$ . In contrast to the three types of residues mentioned above, total contribution of maize straw is relatively small, ranging from 5 to 13% of total emissions for all pollutants considered except for NMVOCs,  $\text{CH}_4$  and  $\text{PM}_{2.5}$ .

### 3.3.3. Variation in CO emissions over the districts

As CO is the most widely studied specie in emission modeling from agricultural burning, it used here as a figurative example to describe the spatial and temporal trends across Pakistan from various crops (Streets et al., 2003a; Li et al., 2016). CO emissions from each district are shown

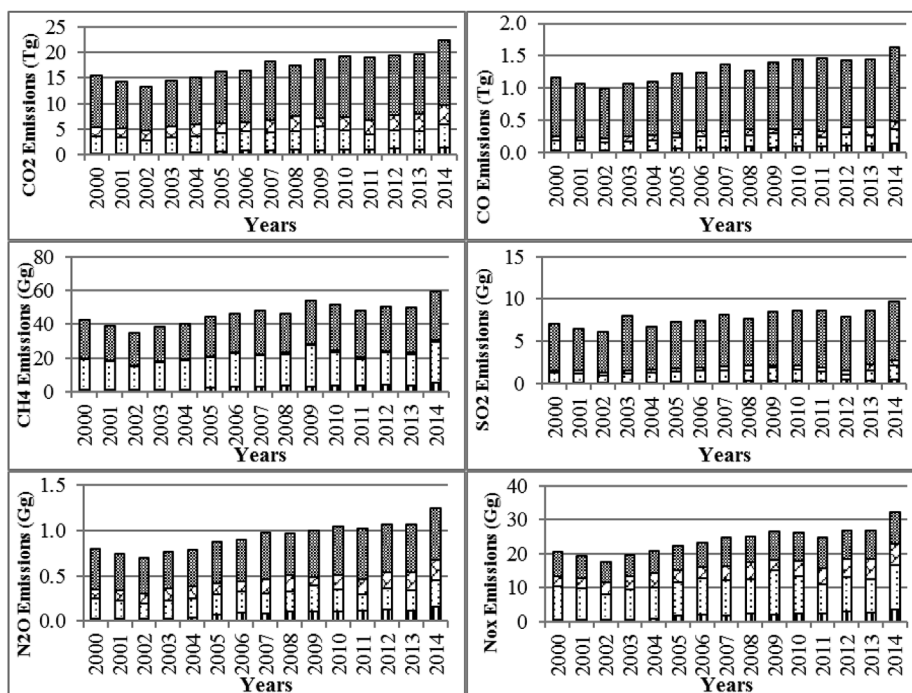


Fig. 12. Annual emission estimates (Tg/Gg) of 12 pollutants considered in this study from 2000 to 2014.

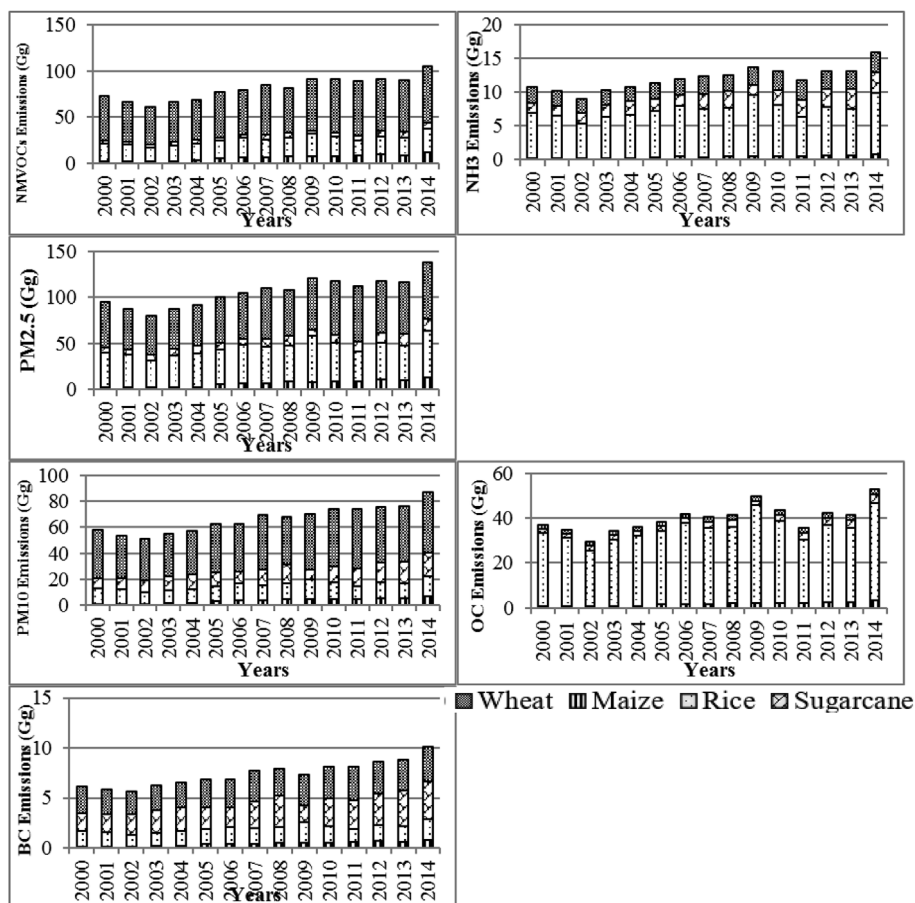


Fig. 12. (continued)

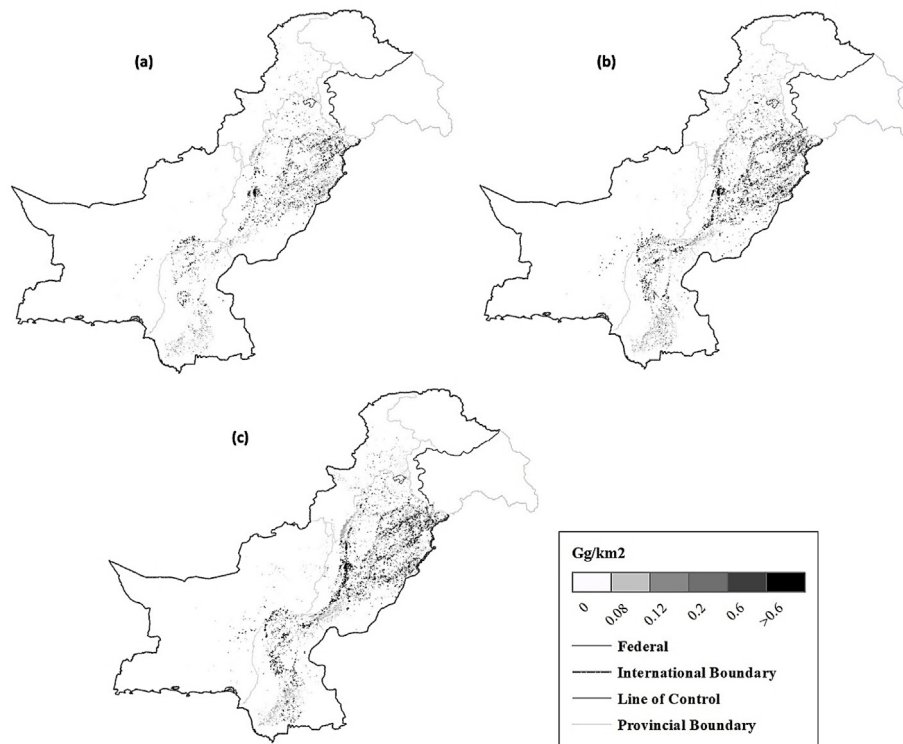


**Fig. 13.** Variations in spatial distribution of CO at a resolution of  $1 \times 1$  km grid cell from burning of crop residues at five-years intervals; (a) 2001–04, (b) 2005–09 and (c) 2010–14.

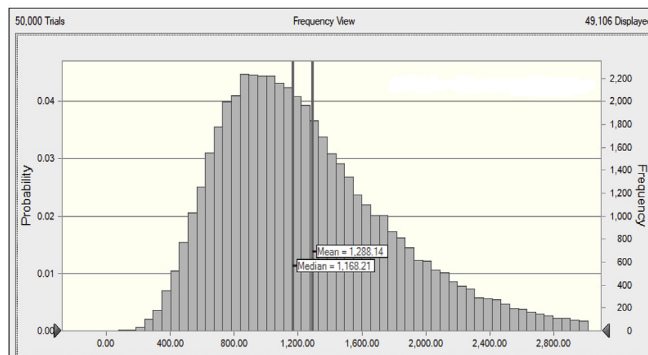


**Fig. 14.** Probability distribution of CO emissions in 2014, with 50,000 Monte Carlo Simulations.

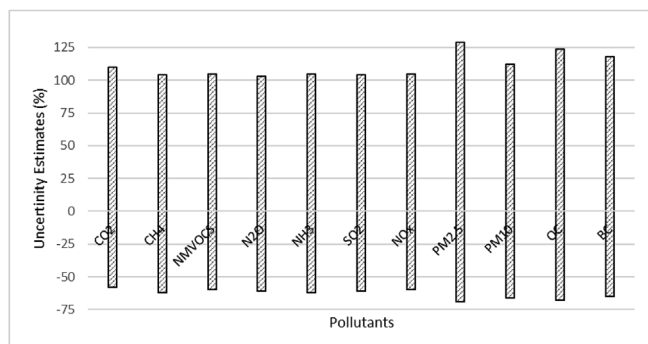


**Fig. 15.** Uncertainties in total emissions estimates for 2014.

in Fig. 8 (Fig. S4 in SI for better viewing). Districts 82 (Muzaffargarh) and 97 (Rahimyar Khan) of southern Punjab had the highest contribution of 10% and 6% respectively of the total national CO emission

in 2014. Districts 113 (Swat), 89 (Nushki), 36 (Harnai) and 96 (Quetta) were the least contributor, sharing around 0.0061% collectively, of total CO emission in the year.

Crop specific CO emissions are shown in Fig. 9 (Fig. S5 in SI for better viewing). Burning of each crop residue was area dependent, with burning of wheat dominating in all districts. Districts 106 (Sheikhupura) and 30 (Gujranwala) showed significant Rice emissions as well due to rice-wheat cropping systems. CO emissions from maize were significant in districts 101 (Sahiwal), 92 (Pakpattan) and 90 (Okara) while Sugarcane emissions were highlighted in districts which are also larger contributor in its production such as 28 (Faisalabad), 16 (Chinniot), 85 (Nankana Sahib) and 43 (Jhang). Fig. S6 (SI) shows district wise crop specific emissions of all pollutants considered.

### 3.3.4. Spatial and temporal distribution of CO emissions in 2014

Spatial distribution of fire occurrences was used for allocation of emissions in grid. Fig. 10a, b and c (and Fig. S7 in SI for better viewing) show the spatial distribution of annual and seasonal CO emissions during year 2014 in a  $1 \times 1$  km grid. CO emissions were denser in agriculture dominated districts of Punjab and Sindh provinces as compared to other areas of Pakistan. Most of the districts had grids of strength up to 0.2 Gg CO emissions. High concentration grids were located in districts 82 (Muzaffar Garh, up to 1.6 Gg/km<sup>2</sup>) followed by 83 (Noshero Feroz, 1.2 Gg/km<sup>2</sup>) and 40 (Jafferabad, 1 Gg/km<sup>2</sup>). Fig. S8 (SI) shows spatial distribution of all considered pollutants in  $1 \times 1$  km grid cell for 2014.

Temporal distribution of CO emissions on the basis of fire counts observed in the months of 2014 is shown in Fig. 11. It was observed that most emissions occurred during October to June with the peak of emission in June which typically refers to harvesting of wheat and maize. The second peak was observed during Jan–March which is the harvesting season of sugarcane whereas the peak observed in October–November refers to rice harvesting season.

**Table 4**  
Comparison with Streets et al. (2003b).

| Reference              | Year | CO <sub>2</sub> | CO   | CH <sub>4</sub> | NMVOCs | NH <sub>3</sub> | SO <sub>2</sub> | OC    | BC     |
|------------------------|------|-----------------|------|-----------------|--------|-----------------|-----------------|-------|--------|
| Streets et al. (2003b) | 2000 | 15.15           | 0.92 | 0.027           | 0.157  | 0.013           | 0.004           | 0.033 | 0.007  |
| This study             | 2000 | 15.5            | 1.16 | 0.043           | 0.073  | 0.011           | 0.0071          | 0.037 | 0.0062 |

**Table 5**  
Comparison with Irfan et al. (2015) <sup>a</sup>.

| Reference           | Year | CO <sub>2</sub> | CO   | CH <sub>4</sub> | NH <sub>3</sub> | SO <sub>2</sub> | NO <sub>x</sub> | OC    | BC     |
|---------------------|------|-----------------|------|-----------------|-----------------|-----------------|-----------------|-------|--------|
| Irfan et al. (2015) | 2007 | 14.79           | 1.18 | 0.0412          | 0.011           | 0.0065          | 0.03151         | 0.017 | 0.0057 |
| This study          | 2007 | 16.12           | 1.19 | 0.0412          | 0.010           | 0.0073          | 0.021           | 0.034 | 0.0068 |

<sup>a</sup> Emissions for Punjab and Sindh provinces are compared only as Irfan et al. (2015) studied these two provinces.

**Table 6**  
Comparison with Iqbal and Goheer (2008).

| Reference               | Years | CO <sub>2</sub> | CH <sub>4</sub> | NO <sub>x</sub> |
|-------------------------|-------|-----------------|-----------------|-----------------|
| Iqbal and Goheer (2008) | 2001  | 16.961          | 0.0299          | 0.1202          |
|                         | 2006  | 19.73           | 0.0354          | 0.14            |
| This study              | 2001  | 14.3            | 0.039           | 0.019           |
|                         | 2006  | 16.5            | 0.046           | 0.023           |

### 3.4. Historical variation in emissions

Historical emissions of 12 pollutants from crop residue burning were calculated for 2000–2014 using eq. (1) and are shown in Fig. 12. CO emissions have increased by 40% (2.7%/year) from 1.16 Tg in 2000 to 1.63 Tg in 2014. Emissions of CO<sub>2</sub>, CH<sub>4</sub>, NMVOCs, N<sub>2</sub>O, NH<sub>3</sub>, SO<sub>2</sub>, NO<sub>x</sub>, PM<sub>2.5</sub>, PM<sub>10</sub>, OC and BC have increased by 44%, 40%, 44%, 55%, 48%, 37%, 55%, 46%, 50%, 43% and 63% respectively. The emissions followed an increasing trend mainly due to increase in production of crops.

#### 3.4.1. Spatial distribution of emissions

As spatial distribution of agricultural fire incidents observed by MODIS were used to grid the emissions over Pakistan in past years, Fig. 13 (and Fig. S9 in SI for better viewing) shows the spatial distribution of CO emissions in five-year composite periods of 2000–2004, 2005–2009 and 2010–2014. The distribution of emissions in the past years was almost similar but the emission intensity has increased with time. The grids with the concentration of about 0.4 Gg are increasing as observed in each composite which indicates that contribution of crop residue burning is increasing with time. CO emissions are mainly scattered around river Indus in districts of Punjab and Sindh provinces with few emission grids located in KPK and Balochistan provinces. Mostly grids in KPK and Balochistan have emission strengths between 0.1 and 0.2 Gg. The high concentration grids are expanding in districts of upper and lower Punjab and upper Sindh with major contribution from districts 82 (Muzaffar Garh) and 83 (Noshoro Feroz) and nearby districts.

### 3.5. Uncertainty estimates

To assess these uncertainties Monte Carlo method is widely used in inventory studies (Li et al., 2016; Zhou et al., 2017). Uncertainty in

emission estimates mostly comes from activity data and emission factors. Activity data incorporates uncertainty from four aspects which include crop production, grain to straw ratio, dry matter content, portion of crop residue burned and combustion efficiency. Coefficient of variation (CV) i.e. standard deviation divided by mean is obtained from the literature (Streets et al., 2003a). Activity data excluding grain to straw ratio is assumed to have normal distribution with 30% CV and grain to straw ratio is assumed to have a uniform distribution (Zhao et al., 2011). Emission factors were assumed to have normal distribution (Streets et al., 2003a) while for PM<sub>2.5</sub>, PM<sub>10</sub>, OC and BC lognormal distribution was assumed (Bond et al., 2004). Probability distribution of data was calculated with 50,000 Monte Carlo simulations at 95% confidence interval. Fig. 14 shows the probability distributions of CO emissions in 2014, mean value, 2.5th and 97.5th percentiles were 1.19, 0.42 and 2.67 Tg respectively. Based on the probability density distributions of activity data uncertainty in total emissions estimated for 2014 is shown in Fig. 15.

### 3.6. Comparison with previous studies and global data sets

So far, few studies have been reported on estimating crop residue burning emissions for Pakistan. However, Streets et al. (2003b) quantified gaseous and aerosols emissions from crop residue burning in Asia for 2000 and estimated emissions for Pakistan. Besides, Irfan et al. (2015) compiled emissions from open burning of rice straw, wheat straw and bagasse for Punjab and Sindh provinces for 2006–07. Similarly, Iqbal and Goheer (2008) estimated total GHG emissions (CO<sub>2</sub>, CH<sub>4</sub> and NO<sub>x</sub>) of Pakistan covering the emissions from four major crop residue burning for year 2001 and 2006. Comparison of the estimates for respective years in this study with the reported work is shown in Table 4, Table 5 and Table 6. These inventories were developed using bottom-up approach. Emissions for common pollutants estimated in this study were comparable with Irfan et al. (2015). However, the emissions for CO, CH<sub>4</sub> and SO<sub>2</sub> estimated in this study for 2000 were higher than those reported by Streets et al., (2003b). Emissions of CO<sub>2</sub> and CH<sub>4</sub> reported by Goheer were close to those reported in this study for overlapping years. However, NO<sub>x</sub> emissions estimated in this study are relatively higher. The difference in estimates is attributed to difference in the emission factors, as Streets et al. (2003b) used combined emission factors for all crop types which were also not region specific (Andreae, 2001). Moreover this study uses updated data set for the estimates of crop residue portion burned on field (18–55% as reported by survey of

**Table 7**  
Comparison with FINN estimates for 2014 (Wiedinmyer et al., 2011).

| Reference  | CO <sub>2</sub> | CO     | CH <sub>4</sub> | NMVOCs | NH <sub>3</sub> | OC     | BC     | PM <sub>2.5</sub> | PM <sub>10</sub> | SO <sub>2</sub> |
|------------|-----------------|--------|-----------------|--------|-----------------|--------|--------|-------------------|------------------|-----------------|
| This Study | 22.4            | 1.63   | 0.059           | 0.105  | 0.016           | 0.053  | 0.01   | 0.138             | 0.087            | 0.0097          |
| FINN       | 25.6593         | 1.8091 | 0.0963          | 0.8996 | 0.0371          | 0.0573 | 0.0112 | 0.1003            | 0.1214           | 0.0070          |

World Bank, 2016) which is supposed to be more accurate than generalized assumption of 25%, made in earlier reported studies. Besides the regional studies, National Center of Atmospheric Research (NCAR) maintains a global Fire Inventory from NCAR (FINN) (Wiedinmyer et al., 2011) which provides high resolution (1 km × 1 km, daily observations) emission estimates for biomass burning. Table 7 shows the comparison of the estimates of the pollutants considered in this study with FINN estimates for 2014. FINN estimates were found to be slightly higher than those of this study for all pollutants (except PM<sub>2.5</sub>), which can be attributed to the fact that FINN estimates are made for all crops whereas this study considered only four major crops of the country.

#### 4. Conclusion

In this study, an improved and updated multi-year (2000–2014) crop residue combustion emission inventory with high spatial and monthly temporal resolution was established for Pakistan using district level crop production and specific emission factors. More accurate data of portions of crop residues burned on field and most recently published locally developed emission factors were incorporated in emission estimations. Four major crop residues i.e. wheat straw, rice straw, maize straw and sugarcane leaves were considered. Total annual emissions of CO<sub>2</sub>, CO, CH<sub>4</sub>, NMVOCs, N<sub>2</sub>O, NH<sub>3</sub>, SO<sub>2</sub>, NO<sub>x</sub>, PM<sub>2.5</sub>, PM<sub>10</sub>, OC and BC in 2014 were 22.4, 1.63, 0.06, 0.105, 0.0012, 0.02, 0.01, 0.032, 0.14, 0.08, 0.05 and 0.01 Tg respectively. Spatially, throughout the study period 2000–2014, Muzaffargarh, Jafferabad, and Noushahro Feroze had the highest emissions as compared to other areas of Pakistan. Temporally crop residue burning was dependent on the harvesting seasons, with highest concentration in May followed by February, November and December. There was significant increase in pollutant emissions over 15 years ranging from 37% for SO<sub>2</sub> to 63% for BC. The observed trend suggested that emissions will continue to rise in future due to absence of policy intervention.

#### Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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#### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.atmosenv.2019.03.031>.

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